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Array-Fed Fabry-Perot Cavity Antenna for Two-Dimensional Beam Steering

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***Abstract*—We propose a simple phased-array design based on a Fabry-Perot cavity antenna for the generation of a highly-directive pencil beam steerable along two directions in 3-D space. Each array element generates an element pattern in the far-field obtained through the excitation of a dominant cylindrical TM leaky wave inside the cavity. Hence, the resulting conical pattern is combined with the array factor of a $N \times N$ square or circular arrangement of ideal vertical electric dipoles. By proper phasing such sources at the operating frequency, a pencil beam with continuous scanning both in azimuth and elevation is achieved. The proposed leaky-wave phased array is of interest for future wireless power transfer systems as well as for advanced radar and localization systems.**

***Index Terms*—Fabry-Perot cavity antennas, leaky-wave antennas, conical patterns, beam steering, arrays.**

I. Introduction

The ever-increasing demand for high-gain, low-cost and low-profile antennas, capable of radiating pencil beams steerable within wide solid angle sectors, calls for the investigation of new antenna solutions. Although the design of digital beam-scanning systems based on multiple arrangements of single elements are nowadays well established, they involve high costs and bulky structures, whose feeding networks can be very complex and expensive [1]. In this contribution we investigate the potential advantages provided by an alternative approach, in which the highly-directional leaky-wave conical element pattern (EP) supported by a Fabry-Perot cavity antenna (FPCA) is transformed into a pencil beam. This is simply obtained by embedding a square or circular array of elementary sources inside the cavity. Thus, such a beam is steered along both the zenith and azimuth directions by changing the operating frequency and by suitably phasing the array of sources, respectively.

As is known, an FPCA consists of a cavity bounded on top by a partially reflecting surface (PRS), in the form of either a uniform dielectric superstrate or a homogenizable, quasi-uniform thin patterned metal screen, and on bottom by a metal ground plane (see, e.g., [2]). The thickness of the cavity mainly controls the pattern shape, which can be either a broadside pencil beam or a conical beam, depending also on the excitation. The feeder essentially works as the launcher of a cylindrical leaky wave inside the cavity, and is typically a simple, non-directive radiator (e.g., a printed patch or dipole), thus resulting in a low-cost design.

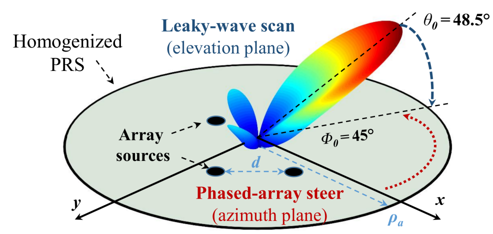

Fig. 1. 3D view of the proposed FPCA fed by a planar array of simple sources. The PRS (in transparency) is made by a homogenizable array of patches. The color scale is linear (dark blu 0, dark red 1).

The use of FPCAs in array configurations has received considerable attention in the last decade (see, e.g., [2]-[4]), and the possibility to obtain scannable beams at a fixed frequency using FPCAs has also been explored by electronically reconfiguring the PRS (see, e.g., [5] and refs. therein). However, in all the considered FPCA arrays, the EP is designed to radiate a directional broadside pencil beam. We propose here the use of FPCAs with *omnidirectional conical scanned patterns* to synthesize a highly-directional pencil beam scannable in both elevation and azimuth (see Fig. 1). This is accomplished through a planar phased array of azimuthally invariant sources radiating inside the considered FPCA, which in turn support a dominant TM cylindrical leaky wave (CLW) of $n = 0$ azimuthal order [6]. This produces a directive omnidirectional conical EP scanning with frequency in the elevation plane. Hence, a reduced number of sources can be arranged to form a phased array radiating a pencil beam with high directivity. As depicted in Fig. 1, flexible 2-D beam-angle reconfigurability can be obtained both in elevation, by varying frequency, and in azimuth, by varying the relative phasing between each element in the array.

II. Antenna Design

We consider an FPCA for Ku/K-band applications, designed to work at a central frequency equal to 15 GHz. The cavity has thickness $h = 14.1$ mm and is completely filled by a homogeneous dielectric medium having effective permittivity $\varepsilon_{r_{\text{eff}}} = 1.2$, which can be practically obtained by drilling a

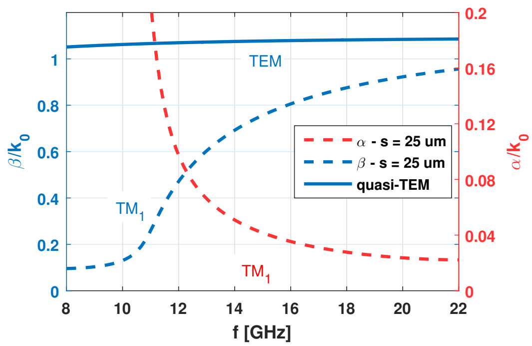

Fig. 2. Normalized dispersion curves for the designed Fabry-Perot cavity.

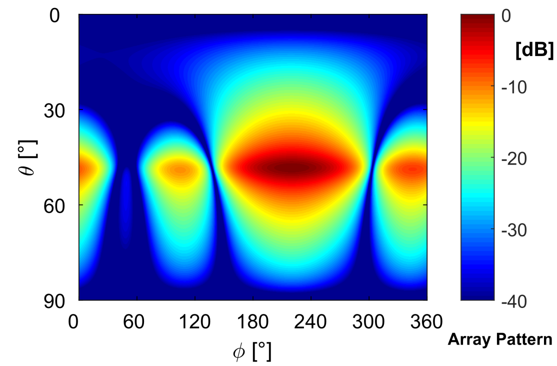

Fig. 3. Normalized radiation pattern (colormaps in the 2-D plane, ϕ vs. θ) for an FPCA array with 2×2 elements, at f = 15 GHz and $\phi_0 = 220°$.

periodic pattern of air holes inside commercially available substrates (with $\varepsilon_r = 2.2$) [1]. The period of the PRS, made by square patches, is $p = 3$ mm and the slot width $s = 25$ μm, which is mainly dictated by manufacturing constraints.

As is well-known, to a first-order approximation, s mainly controls the attenuation constant α of the radially-propagating leaky modes, which determines the beamwidth of the EP in the elevation plane and, thus, its directivity [7]. Furthermore, assuming that the radial dimensions of the substrate are designed to radiate at least 90% of the power injected into the TM leaky mode [7], the value of α also indirectly determines the dimensions of the entire structure (here $\rho_a = 11$ cm = $5.5\lambda_0$). The FPCA is excited with an elementary azimuthally invariant source, i.e., a vertical electric dipole (VED) placed along the z-axis on top of the ground plane, which is able to effectively model a coaxial cable penetrating the cavity [8].

An exact evaluation of the EP produced by the VED in the presence of the FPCA can be obtained by either using a well-known approach based on the reciprocity theorem, valid for arbitrary multi-layered infinite open structures (see, e.g., [9] and refs. therein), or by using the closed-form expressions of the far-field radiated by the dominant CLW aperture field [6], in conjunction with the complex wavenumber of the TM leaky mode supported by the linearized FPCA. We consider here the latter method, capable of generating the desired azimuthally invariant leaky-wave pattern $EP^{\text{LW}}(\theta)$. The array factor $AF(\theta, \phi)$ is calculated by means of standard array theory [1]. The resulting pencil-beam pattern radiated by the array-fed FPCA is then given by $F^{\text{array}}(\theta, \phi) = AF(\theta, \phi)EP^{\text{LW}}(\theta)$. As a test case, we consider here a simple configuration made by a square arrangement of a 2×2 VEDs placed at a distance $d = 8$ mm (properly selected to avoid the appearance of grating lobes), whose AF can be equivalently calculated by means of the rectangular or circular formulation [1]. More complex rectangular or circular array source arrangements are possible and can be evaluated using the proposed approach.

III. Numerical Results

A dispersive analysis for the designed FPCA has been conducted by means of a transverse equivalent network (see, e.g., [9]). The dispersion curves of the normalized phase and attenuation constants, i.e., β/k_0 and α/k_0, for the quasi-TEM and TM$_1$ modes are reported in Fig. 2. As desired, the quasi-TEM is a slow wave, not contributing to the far-field [8], [9]. Hence the EP is supported by the TM$_1$ leaky mode, which is fast and leaks power while traveling towards the aperture truncation. Fig. 3 reports 2-D plots of the normalized radiation pattern of the designed FPCA, phasing the 4 sources to direct the resulting pencil beam at an azimuthal angle $\phi_0 = 220°$, while the elevation angle (controlled by β) at 15 GHz is equal to $\theta_0 = 48.5°$. The plot in Fig. 1 reports a 3-D representation of the pencil beam, at the same frequency, phasing to radiate at $\phi_0 = 45°$. To account for the mutual coupling between the sources, full-wave validations have been developed. The resulting pattern directivity has been compared to the same VED array above a ground and no top PRS, showing a clear reduction of the total number of sources (about 10 times less). Experimental validations on a manufactured prototype are in progress and will be presented at the conference.

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